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SUN COMPASS ERROR MODEL

Mathematical Physics Branch

MISSION PLANNING AND ANALYSIS DIVISION



MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

SUN COMPASS ERROR MODEL

By T. J. Blucker, Mathematical Physics Branch,
and W. W. Ferry, TRW Systems Group

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CONTENTS

Section		Page
1.0	SUMMARY	1
2.0	INTRODUCTION	1
3.0	DISCUSSION	2
	3.1 Error Model Description	2
	3.2 Sun Compass Field Test	4
4.0	CONCLUSIONS	6

TABLES

Table		Page
I	LANDMARK SIGHTING DATA	
	(a) Landmark number 1 (MSC building number 32)	7
	(b) Landmark number 2 (MSC water tower)	8
	(c) Landmark number 3 (double water towers)	9
	(d) Clear Lake water tower	10
	(e) Clear Lake Hospital	11
	(f) Nassau Bay water tower	12
II	SUN AZIMUTH AND ELEVATION ANGLE RATES	13
III	INDIVIDUAL OBSERVER STATISTICS	14

SUN COMPASS ERROR MODEL

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1.0 SUMMARY

An error model is described for the Apollo 15 sun compass, a contingency navigational device. Field test data are presented along with significant results of the test. The errors reported include a random error resulting from tilt in leveling the sun compass, a random error because of observer sighting inaccuracies, a bias error because of mean tilt in compass leveling, a bias error in the sun compass itself, and a bias error because the device is leveled to the local terrain slope.

2.0 INTRODUCTION

The Apollo 15 crew will have available for contingency navigation a sun compass under development by the Flight Crew Support Division. This device is used to measure the azimuth of known lunar landmarks to provide an observer position fix and also to supply a heading direction for guiding the return to the LM. The Mathematical Physics Branch has completed a study under TRW task A-169 to define an error model for this sun compass instrument.

A proposed error model for the sun compass angle readout includes the following additive terms.

- a. A random error, independent of landmark azimuth, caused by observer sighting error and readout quantization
- b. A random error, dependent on landmark azimuth, caused by a random tilt in leveling the sun compass
- c. A bias error, dependent on landmark azimuth, caused by a mean tilt introduced by the observer in leveling the device

- d. A bias error in the sun compass, independent of landmark azimuth
- e. A bias error, independent of landmark azimuth, caused by leveling the device by reference to the local terrain slope

This error model assumes a mechanical leveling aid is not included with the device.

A sun compass, representative of the one to be included on Apollo 15, was obtained and a "field" test of the device was conducted at the Manned Spacecraft Center (MSC), which consisted of seven observers taking sightings on surveyed landmarks, with the sun elevation angle in the approximate range defined for the Apollo 15 lunar traverses (15° to 25°). The significant results of the test were as follows.

- a. Repeated handling of the device caused the vertical flap (shadow generator) to become dislodged from its restraint, a condition which went unnoticed by several observers. This structural perturbation introduced an estimated 4° to 8° azimuth readout error and consequently it is recommended that the flap position be verified prior to each set of sightings.
- b. The mean error for the total sighting set was 2.3° .
- c. The standard deviation for the sightings on each landmark varied from 0.99° to 2.29° with a total root mean square (RMS) value of 1.60° .
- d. The test provided no quantitative data for the bias errors caused by a leveling error. However, it was noticed that individual observers will introduce several degrees of pitch tilt in the device because of poor leveling cues about the horizontal axis perpendicular to the sighting line of sight (LOS). For a sun elevation of 25° , the maximum azimuth error is approximately 40 percent of the leveling tilt.

3.0 DISCUSSION

3.1 Error Model Description

The sun compass intended for use on the Apollo 15 lunar surface traverses is a hand-held device for measuring the azimuth of a landmark relative to a reference line (probably lunar north). The observer holds the device approximately chest high in a level orientation and points a reference line toward the desired landmark. A disk, to which is attached a vertical flap for projecting the shadow of the sun, is then rotated to align the shadow edge with a predetermined point on the disk. The azimuth

angle is finally read off the disk at the point of intersection with the sighting reference line. It is presently not certain if the sun compass will be outfitted with a mechanical leveling aid (most likely a dome bubble level).

A proposed error model for the sun compass azimuth readout, assuming no leveling aid, is presented in the following expression.

$$\Delta\theta_A = \eta_s + \eta_\theta + b_\theta + b_s + b_t$$

where

$\Delta\theta_A$ = the error in the measured azimuth angle

η_s = a random error caused by the observer azimuth pointing deviation and sun compass readout quantization. This term is assumed to be independent of landmark azimuth.

η_θ = a random error caused by a random tilt in leveling the sun compass. Without a leveling aid, an observer can still adjust the level about the sighting LOS axis by equalizing his hand height. Leveling the device about the axis perpendicular to the LOS (pitch axis) is considerably more difficult because of poor leveling cues. Assuming the total random leveling error is essentially in pitch, the azimuth error is given by

$$\eta_\theta = T_A \tan \alpha \sin (\theta - \beta) \quad (1)^a$$

where

T_A = random pitch angle tilt

α = sun elevation angle

$\theta - \beta$ = difference between landmark azimuth and sun azimuth

^aThis expression was developed by L. J. Miller, TRW Systems Group.

The error term η_θ is azimuth dependent as expressed in equation (1), with a maximum value for sighting perpendicular to the sun azimuth. Also, T_A may have a larger variance for sightings in the down-sun quadrants because the device must be held up and away from the body to avoid the observer's shadow.

b_θ = a bias error term caused by a mean pitch tilt introduced by the observer in leveling the device. The expression for b_θ is given in equation (1), where T_A now represents the mean pitch angle. The inclusion of this error term was motivated by the fact that an astronaut may have to operate the sun compass in a bent posture which could induce a mean tilt.

b_s = a bias error term contributed by the sun compass and independent of sighting azimuth

b_t = a bias error term caused by leveling the device by reference to the local terrain slope. The azimuth error is given by an expression similar to equation (1).

$$b_t = \delta_s \tan \alpha \sin \phi \quad (2)$$

where

δ_s = terrain slope

ϕ = angle between sun azimuth and terrain slope gradient

3.2 Sun Compass Field Test

In order to generate some statistical data for the sun compass error model, a field test was conducted on the device. The test sightings were performed by seven observers in a field behind MSC building 14 on May 11, 1971, in the time interval from 0800 to 0910 c.d.t. The sun elevation angle during this time varied from approximately 18° to 33° . Sightings were made on the following set of six landmarks (LMK).

LMK no. 1 - MSC building no. 32

LMK no. 2 - MSC water tower

LMK no. 3 - double water towers

LMK no. 4 - Clear Lake water tower

LMK no. 5 - Clear Lake Hospital

LMK no. 6 - Nassau Bay water tower

The "true" landmark azimuths were determined using a transit and are presented in figure 1. The sun azimuth and elevation angles were also measured at selected time points. A reference azimuth was defined as 90° = sun azimuth at 0830 c.d.t.

The basic sighting schedule consisted of each observer, in turn performing a single azimuth measurement on each of the six landmarks. The sequence was repeated twice for a total of 126 sightings (7 observers times 3 sightings times 6 landmarks). It was discovered, however, during the third sequence of sightings that the vertical flap on the sun compass had become dislodged from its restraint, introducing several degrees of bias in the data. An investigation of the sighting data for that round indicated that the misadjustment was unnoticed by several observers. Consequently, the data for that round were not included in the statistical analysis, leaving two sightings per observer per landmark.

The sighting data for each landmark are presented in table I. Listed first are the individual observer, the measurement time, and the raw (uncompensated) azimuth angle readout. To compensate for the time-varying sun azimuth, each sighting angle was converted to a measurement taken at 0830 c.d.t. using the sun azimuth rate computed in table II from transit readings. The resultant compensated angle is then the landmark azimuth measured relative to the previously defined 90° reference azimuth. The average of the 14 sightings on each landmark is given in the batch summary together with the mean difference from the transit determined ("true") azimuth. The mean square (MS) deviation from the batch mean for each observer's sightings was then tabulated and a batch standard deviation computed for the summary.

Plots of the mean and standard deviation for the sighting error on each landmark are given in figure 2. The average error for the total sighting set was 2.3° . Making the reasonable assumptions that the local terrain was level and individual observer leveling biases averaged out, the mean sighting error can be attributed to the sun compass.

The standard deviation for the sightings on each landmark varied from 0.99° to 2.29° with a total RMS value of 1.60° . The batch standard deviations tended to be larger for sighting azimuths cross-sun (LMK no. 3 and LMK no. 6), and also showed an increase for sightings in the down-sun quadrants (LMK no. 4, no. 5, and no. 6). These variations with azimuth appear to correspond to the predicted effects of the random tilt error previously discussed in the error model.

The standard deviation for the sightings taken by each observer are given in table III. The data show fairly good consistency among observers (except for Mr. Stimmel whose efforts shall not be criticized since he drove) and indicate a high correlation between sighting accuracy and the time interval in which the observations were taken.

4.0 CONCLUSIONS

An error model for the Apollo 15 lunar surface contingency navigation sun compass has been presented. The errors reported include a random error due to tilt in leveling, a random error due to observer sighting, a bias error due to mean tilt in leveling, a bias error in the sun compass itself, and a bias error due to leveling the device to the local terrain slope.

TABLE I. - LANDMARK SIGHTING DATA

(a) Landmark number 1 (MSC building number 32)

OBSERVER	TIME	SIGHTING ANGLE (DEG)		MS* DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0800	72.75	69.42	0.43
	0822	69.00	68.11	
J. Blucker	0805	71.00	68.23	0.21
	0825	69.00	68.45	
L. Miller	0807	70.00	67.45	1.39
	0828	70.00	69.78	
M. Gelberg	0809	72.00	69.67	3.08
	0831	71.00	71.11	
S. Crigler	0812	70.50	68.50	0.15
	0833	68.00	68.33	
W. Ferry	0815	70.00	68.34	0.38
	0837	68.75	69.53	
T. Stimmel	0820	69.67	68.56	0.76
	0842	66.25	67.58	

BATCH SUMMARY:

Mean Sighting Angle = 68.79 deg.

True LMK Azimuth = 66.18 deg.

Mean Sighting Error = 2.61 deg.

Standard Deviation = 0.99 deg.

*Mean - Square

TABLE I. - LANDMARK SIGHTING DATA - Continued

(b) Landmark number 2 (MSC water tower)

OBSERVER	TIME	SIGHTING ANGLE (DEG.)		MS DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0801	47.50	44.28	1.54
	0823	43.50	42.72	
J. Blucker	0805	45.00	42.33	1.98
	0825	41.00	40.56	
L. Miller	0807	45.50	42.95	0.87
	0829	44.00	43.79	
M. Gelberg	0810	46.50	44.28	1.61
	0831	42.00	42.11	
S. Crigler	0813	45.50	43.61	0.58
	0834	42.00	42.44	
W. Ferry	0815	44.50	42.84	0.70
	0838	40.50	41.39	
T. Stimmel	0820	41.00	39.89	3.52
	0842	41.00	42.33	

BATCH SUMMARY:

Mean Sighting Angle = 42.54 deg.

True LMK Azimuth = 40.02 deg.

Mean Sighting Error = 2.52 deg.

Standard Deviation = 1.29 deg.

TABLE I. - LANDMARK SIGHTING DATA - Continued

(c) Landmark number 3 (double water towers)

OBSERVER	TIME	SIGHTING ANGLE (DEG)		MS DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0802	19.0	15.89	1.65
	0823	14.5	13.72	
J. Blucker	0806	14.0	11.34	5.07
	0826	13.0	12.56	
L. Miller	0807	20.0	17.45	6.36
	0829	15.5	15.39	
M. Gelberg	0810	17.5	15.28	0.74
	0832	14.25	14.47	
S. Crigler	0813	17.0	15.11	1.05
	0835	12.5	13.06	
W. Ferry	0816	15.5	13.95	0.95
	0839	11.75	12.75	
T. Stimmel	0821	14.0	13.00	0.72
	0843	12.25	13.69	

BATCH SUMMARY:

Mean Sighting Angle = 14.12 deg.

True LMK Azimuth = 11.07 deg.

Mean Sighting Error = 3.05 deg.

Standard Deviation = 1.60 deg.

TABLE I. - LANDMARK SIGHTING DATA - Continued

(d) Clear Lake water tower

OBSERVER	TIME	SIGHTING ANGLE (DEG.)		MS DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0803	296.0	293.0	0.44
	0824	294.0	293.3	
J. Blucker	0806	294.0	291.34	1.16
	0826	292.0	291.56	
L. Miller	0808	297.0	294.45	2.96
	0830	294.0	294.00	
M. Gelberg	0811	295.75	293.64	0.87
	0832	293.0	293.22	
S. Crigler	0814	294.5	292.72	0.03
	0836	292.0	292.67	
W. Ferry	0816	294.0	292.45	0.10
	0840	290.75	292.97	
T. Stimmel	0821	291.75	290.75	7.11
	0843	287.75	289.19	

BATCH SUMMARY:

Mean Sighting Angle = 292.52 deg.

True LMK Azimuth = 290.82 deg.

Mean Sighting Error = 1.70 deg.

Standard Deviation = 1.40 deg.

TABLE I. - LANDMARK SIGHTING DATA - Continued

(e) Clear Lake Hospital

OBSERVER	TIME	SIGHTING ANGLE (DEG.)		MS DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0803	254.0	251.00	1.99
	0824	251.0	250.33	
J. Blucker	0806	252.0	249.34	0.27
	0826	249.0	248.56	
L. Miller	0808	252.0	249.56	0.28
	0830	250.0	250.00	
M. Gelberg	0811	252.5	250.39	2.96
	0832	251.25	251.47	
S. Crigler	0814	251.0	249.22	0.20
	0836	248.0	248.67	
W. Ferry	0816	251.0	249.45	2.95
	0840	249.5	251.72	
T. Stimmel	0821	247.0	246.00	17.22
	0843	243.0	244.44	

BATCH SUMMARY:

Mean Sighting Angle = 249.29 deg.

True LMK Azimuth = 246.90 deg.

Mean Sighting Error = 2.39 deg.

Standard Deviation = 2.00 deg.

TABLE I. - LANDMARK SIGHTING DATA - Concluded

(f) Nassau Bay water tower

OBSERVER	TIME	SIGHTING ANGLE (DEG.)		MS DEVIATION FROM BATCH MEAN (DEG ²)
		UNCOMPENSATED	COMPENSATED	
J. Dashiell	0804	203.0	200.11	2.90
	0825	199.5	198.95	
J. Blucker	0807	202.0	199.45	1.95
	0827	197.0	196.67	
L. Miller	0808	201.0	198.56	0.53
	0831	197.0	197.11	
M. Gelberg	0812	202.0	200.00	3.96
	0833	199.5	199.83	
S. Crigler	0815	200.0	198.34	6.74
	0837	193.5	194.28	
W. Ferry	0817	200.5	199.06	3.27
	0841	199.0	200.22	
T. Stimmel	0822	196.0	195.11	14.68
	0844	191.75	193.30	

BATCH SUMMARY:

Mean Sighting Angle = 197.93 deg.

True LMK Azimuth = 196.17 deg.

Mean Sighting Error = 1.76 deg.

Standard Deviation = 2.29 deg.

TABLE II. - SUN AZIMUTH AND ELEVATION ANGLE RATES

● AZIMUTH ANGLE

TRANSIT SIGHTING	TIME	AZIMUTH ANGLE (θ_A)	$\frac{\Delta\theta_A}{\Delta T}$
#1	0832	77.15 deg.	—
#2	0841	78.12 deg.	.107 deg/min
#3	0850	79.13 deg.	.112 deg/min
#4	0900	80.25 deg.	.112 deg/min
Average Rate = 0.111 deg/min			

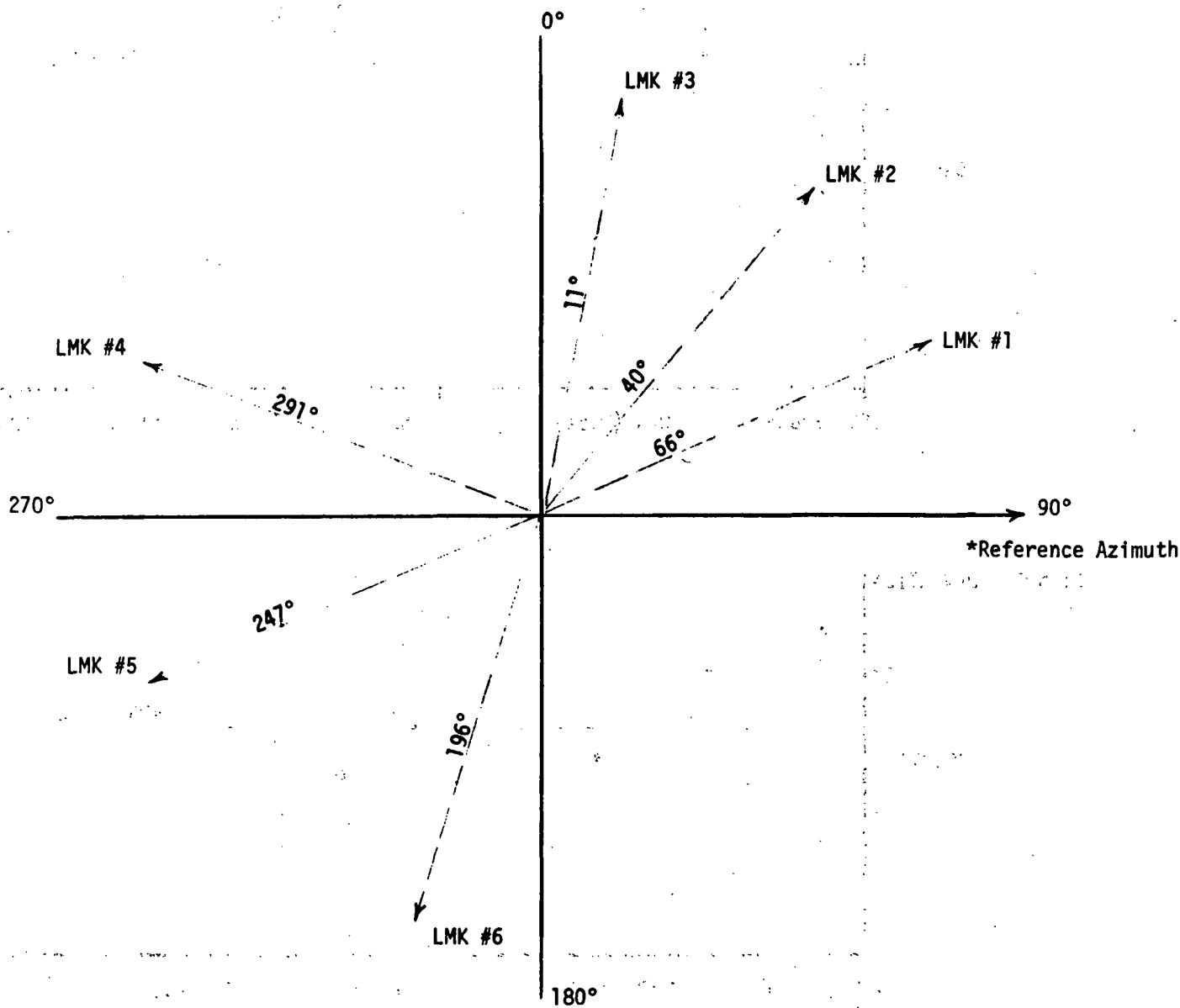
● ELEVATION ANGLE

TRANSIT SIGHTING	TIME	ELEVATION ANGLE (θ_E)	$\frac{\Delta\theta_E}{\Delta T}$
#1	0832	25.00 deg.	—
#2	0841	25.87 deg.	.208 deg/min
#3	0850	28.83	.218 deg/min
#4	0900	30.95	.212 deg/min
Average Rate = .213 deg/min			

TABLE III. - INDIVIDUAL OBSERVER STATISTICS

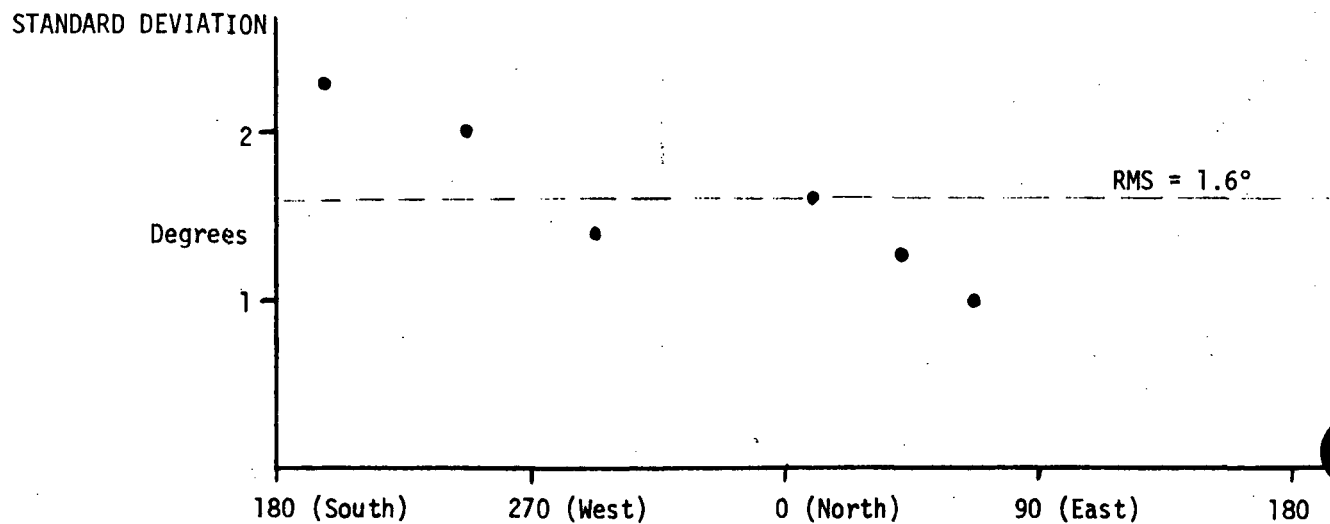
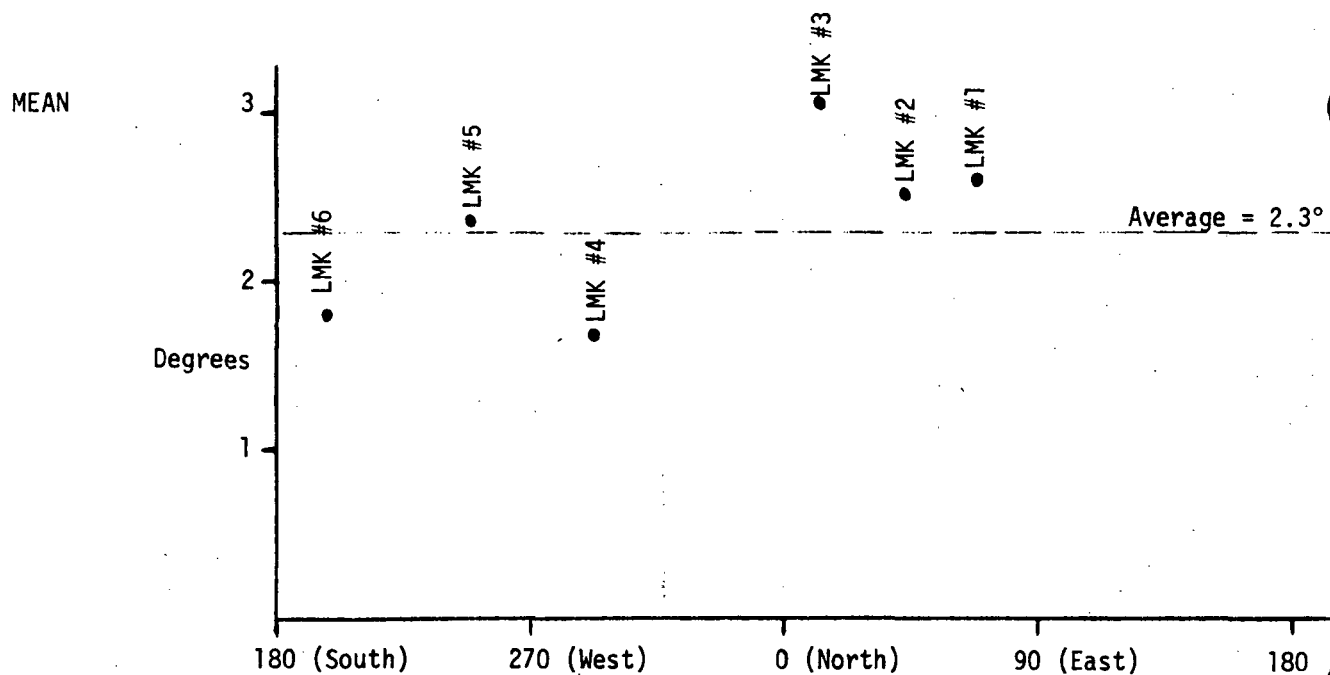
OBSERVER	SIGHTING TIME INTERVAL	*SIGHTING ERROR STANDARD DEVIATION
W. Ferry	8 min.	1.18 deg.
S. Crigler	7 min.	1.21 deg.
J. Dashiell	8 min.	1.22 deg.
J. Blucker	5 min.	1.33 deg.
L. Miller	4 min.	1.44 deg.
M. Gelberg	5 min.	1.48 deg.
T. Stimmel	4 min.	2.71 deg.

*The standard deviation is computed as the RMS deviation from the batch means for two sightings on each of the six landmarks.



*The Reference Azimuth is defined as the Sun Azimuth
at 0830 CDT on 11 May 1971.

Figure 1.- Landmark sighting geometry.



LANDMARK AZIMUTH-DEGREES

(Reference Azimuth : 90° (East) = Sun Azimuth at
0830 CDT, 11 May 1971.)

Figure 2.- Mean and standard deviation for sighting error on each landmark.